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Maximum power point tracking control of direct methanol fuel cells

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HIGHLIGHTS

- The existence of flow rate threshold to a DMFC stack is revealed.
- A fitting model of current density and maximum power density is constructed.
- A controller is designed to keep DMFC working at MPPs followed by the load.

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ABSTRACT

The performance of a direct methanol fuel cell (DMFC) is closely related to its operating conditions, and there is a specific combination of operating conditions at which the DMFC produces maximum power. Working at the maximum power point (MPP) can lower the methanol crossover rate and ancillary power consumption, improving the global efficiency of the system. The fuzzy controller proposed in this paper provides a simple and robust way to keep the DMFC working at the MPP by adjusting the operating conditions followed by the variation of the driven load in real time. Simulation shows that the fuzzy control approach can yield satisfactory results.

1. Introduction

Currently, direct methanol fuel cells (DMFCs) are a highly promising alternative power source, with their most attractive feature being the use of liquid methanol fuel. However, its lower efficiency and power density limits the application of DMFCs [1]. To achieve better performance, many researchers have studied DMFCs by experimental and numerical methods [2–15]. Their findings have shown that the DMFC performance can be improved significantly by tuning the operating conditions closely related to methanol crossover and efficiency, such as temperature, methanol concentration and current density.

The power produced by the DMFC varies with the driven load under the same operation conditions, and there always exists an operating point at which the DMFC can produce the maximum power. This operating point is called the maximum power point (MPP), which varies with the operating conditions. Although the fuel efficiency is 50% at best at the MPP, it is still beneficial for applications where power density is more important than fuel efficiency [16]. Zhong et al. [16] designed an adaptive extremum-seeking controller to trace the MPPs of fuel cell power plants. Chun et al. [17] proposed a novel approach combining a radial basis function neural network and particle swarm to determine the MPP of a small wind power generator system. Although MPP tracking (MPPT) methods have been widely used in photovoltaic, wind, and PEMFC applications [16–20], few studies about MPPT have been reported to date.

This paper studied the relationship between operating conditions and MPPs based on a DMFC model to determine suitable control variables and to find an effective optimum operating strategy. It also proposed a controller design to force a DMFC to work at its MPP to improve the performance and efficiency of DMFCs by adjusting the operating conditions.

The paper is organized as follows. In Section 2, the relationship between MPP and operating conditions is discussed. A fuzzy controller for controlling the current density and concentration is introduced in Section 3, and the simulation results are discussed in detail in Section 4.

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2. Relationships between operating conditions and MPP

In this work, three easily controlled operating conditions are selected as control variants to study the DMFC performance based on a DMFC model described in Ref. [8]: current density, methanol concentration, and flow rate. The other main operating conditions are defined as follows:

1. The fuel cell stack temperature is kept at 353 K.
2. The methanol/water solution is fed into anode under ambient pressure (0.1 Mpa).
3. The air is fed into cathode at elevated pressure (0.3 Mpa).
4. The air flow rate is proportional to the methanol concentration fed into the anode, the stoichiometry of air and methanol is kept at 2.

To determine the MPPs of the DMFC, we first selected various combinations of methanol concentration and flow rate and then adjusted the current density manually to obtain the maximum power density and the corresponding methanol crossover rate. Table 1 presents the simulation results of maximum power density, voltage, current density, and crossover rate under different combinations of concentration (0.1–2 M) and flow rate (2–30 ml min^{-1}).

To determine the effects of different operating conditions on the performance of DMFC, we also calculated the correlation coefficients by SPSS based on the data sets shown in Table 1, and the results are presented in Table 2.

Table 1
The performance of MPP and the corresponded operating conditions.

	Flow rate (mL min^{-1})	Concentration (M)	Current (mA cm^{-2})	Max power (mW cm^{-2})	Crossover rate (mol $cm^{-2}s^{-1}$)
1	2	0.1	24	12.61	6.79E–06
2	5	0.1	24	13.7	1.44E–05
3	10	0.1	25	14.04	1.29E–05
4	20	0.1	25	14.19	1.42E–05
5	30	0.1	26	14.24	1.07E–05
6	2	0.2	46	25.37	2.23E–05
7	5	0.2	48	27.05	2.87E–05
8	10	0.2	50	27.71	2.58E–05
9	20	0.2	51	28.02	2.45E–05
10	30	0.2	51	28.14	2.54E–05
11	2	0.5	113	61.16	6.42E–05
12	5	0.5	120	65.06	7.14E–05
13	10	0.5	125	66.48	6.43E–05
14	20	0.5	125	67.23	7.10E–05
15	30	0.5	127	67.47	6.53E–05
16	2	0.8	180	94.36	1.06E–04
17	5	0.8	195	100	1.02E–04
18	10	0.8	200	102	1.03E–04
19	20	0.8	200	103.3	1.13E–04
20	30	0.8	205	103.4	9.71E–05
21	2	1	227	115	1.23E–04
22	5	1	240	122	1.42E–04
23	10	1	250	124.2	1.28E–04
24	20	1	250	125.7	1.41E–04
25	30	1	250	126.2	1.46E–04
26	2	1.2	270	134.9	1.58E–04
27	5	1.2	280	142.7	2.03E–04
28	10	1.2	295	145.5	1.73E–04
29	20	1.2	300	146.9	1.69E–04
30	30	1.2	295	147.6	1.94E–04
31	2	1.5	330	163.2	2.29E–04
32	5	1.5	355	172.1	2.33E–04
33	10	1.5	365	175.3	2.31E–04
34	20	1.5	370	177	2.31E–04
35	30	1.5	375	177.3	2.18E–04
36	2	2	430	206	3.47E–04
37	5	2	450	216.6	4.04E–04
38	10	2	470	220	3.73E–04
39	20	2	486	222	3.35E–04
40	30	2	485	223	3.48E–04

2.1. Relationship between current density and maximum power density

The correlation parameters of current density to maximum power density and crossover rate are 0.997 and 0.967, respectively, with a p-value <0.001, which means the current density is significantly related to the maximum power density and crossover rate. Based on the data listed in Table 1, a fitting model of current density and maximum power density was created by MATLAB, defined as follows:

$$I_{\mathrm{Ref}} = 0.002{*}P^2 + 1.688{*}P + 0.336 \tag{1}$$

where i_{Ref} (mA cm^{-2}) is the fitting current density that is most appropriate for the driven load and P (mW cm^{-2}) is the power density calculated by Eq. (2):

$$P = P_{\mathrm{Load}}/A \tag{2}$$

where P_{Load} (mW) is the power of the driven load and A (cm^2) is the cross-sectional electrode area of the DMFC.

Fig. 1 shows the comparison of the simulation results listed in Table 1 and fitting values calculated by Eq. (2). It is obvious that the fitting model can precisely describe the relationship between current density and maximum power density. If the driven load is determined, we can calculate a corresponding current density that can allow the DMFC to operate at an appropriate MPP.

2.2. Relationship between flow rate and maximum power density

The correlation parameter of flow rate to maximum power density is only 0.214 and p is 0.057, which means that the flow rate is unrelated to the power density. Based on data in Table 1, we can find that a change in flow rate can only substantially affect the maximum power density when it is below 20 ml min^{-1}.

According to the operating principle of DMFC, methanol is transferred from the anode channel to the catalyst layer based on the diffusive and convective transport mechanism, where methanol is oxidized and chemical energy is converted into electrical energy. The maximum flux of methanol transferred to the catalyst layer limits the maximum power output of DMFC. The distribution of methanol becomes more uniform with increasing the methanol flow rate [21], which increases the flux of methanol to the catalyst layer by increasing the methanol concentration in the anode channel close to the outlet. But when the distribution of methanol is uniform in the whole channel, the methanol flux will not increase with the flow rate any more.

The data in Table 1 also show that concentration and flow rate are coupled. Indeed, the lack of fuel caused by the reduction of the methanol concentration can be offset by an increase in the flow rate

Table 2
Correlation analysis between operating conditions and performance.

		Max power	Crossover
Current	Pearson correlation	0.997**	0.967**
	Significance	0.000	0.000
Concentration	Pearson correlation	0.893**	0.912**
	Significance	0.000	0.000
Flow rate	Pearson correlation	0.214	0.128
	Significance	0.057	0.257

** Correlation is significant at the 0.01 level (2-tailed).

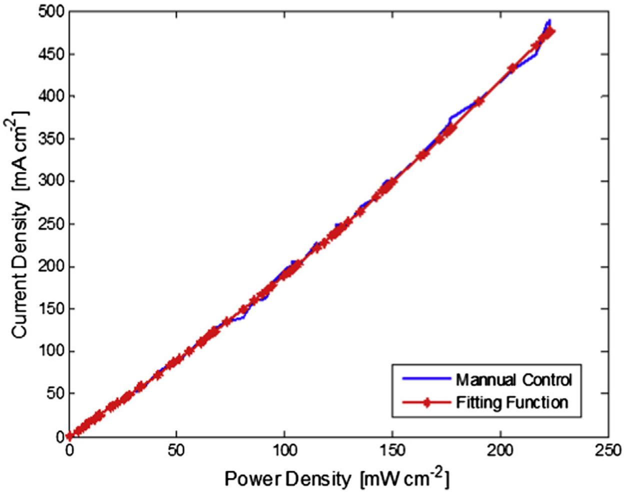
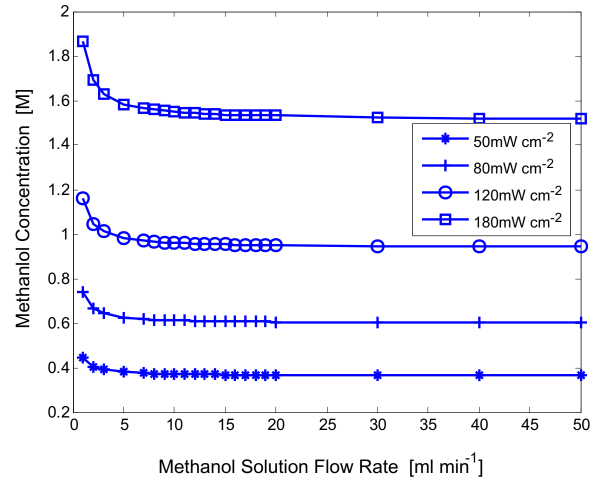
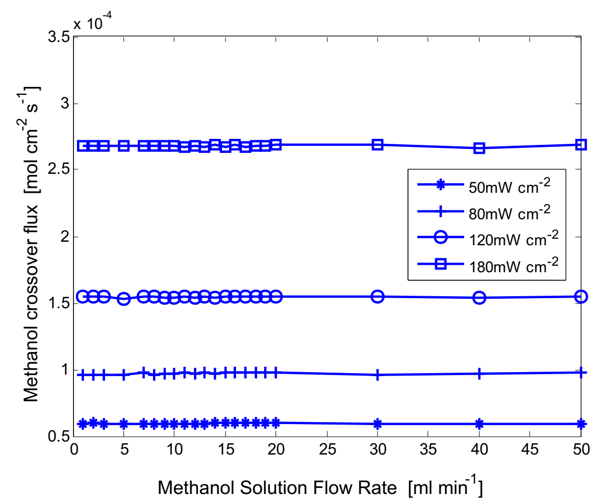


Fig. 1. Comparison of simulation results and fitting values.



(a) the relationship between concentration and flow rate



(b) the relationship between crossover and flow rate

Fig. 2. Effect of flow rate under constant power density.

within the flow rate threshold, as both parameters influence the supply of fuel and vice versa. Fig. 2 illustrates the effect of flow rate on the methanol concentration and crossover rate under different constant power densities. The current density is calculated using Eq. (1) to maintain the DMFC at the MPP.

Fig. 2(a) shows the decrease in concentration with the increase in flow rate under different power densities, and the concentration is almost constant when the flow rate exceeds 20 ml min^{-1}. The decrease in concentration is less than 0.7% when the flow rate increases from 20 ml min^{-1}–50 ml min^{-1} under an arbitrary constant power density; thus, the upper limit of the flow rate should be 20 ml min^{-1}. We also notice that the increase in flow rate causes a significant drop in concentration when the flow rate is below 5 ml min^{-1}. In this region, small fluctuations in the flow rate will cause concentration fluctuations, placing the control system into an unstable state. In addition, the data in Table 1 indicate that a lower flow rate limits the maximum power density for the mass transport limitations of methanol to the anode catalyst layer [5,22]. Therefore, the lower limit of the flow rate should be 5 ml min^{-1}.

In Fig. 2(b), it can be seen that the crossover rate fluctuates slightly with increasing flow rate, and the maximum fluctuation ratio is only 1.6% for flow rates from 1 ml min^{-1}–50 ml min^{-1}. This implies the effect of flow rate on crossover rate under constant power density can be neglected. Ancillary power consumption and control system stability are the main factors determining the flow rate. Although a lower flow rate leads to less ancillary power consumption, the flow rate should be higher than 10 ml min^{-1} based on the effect of carbon dioxide in the anode on the DMFC performance [5]. As discussed above, the suitable flow rate can be set as a fixed value between 10 ml min^{-1} and 20 ml min^{-1} in a DMFC MPPT system. In this paper, a flow rate of 12 ml min^{-1} is selected to minimize power consumption and to maintain better cell performance at the same time.

2.3. *Relationship between methanol concentration and maximum power density*

The correlation parameters for concentration and maximum power density and crossover rate in Table 2 indicate that concentration is also a significant factor affecting both power density and methanol crossover rate.

Fig. 3 illustrates the relationship between the concentration and maximum power density under different flow rates. As can be seen from this figure, we can note that a one-to-one correspondence exists between the concentration and the maximum power density when the flow rate is fixed. An increase in flow rate has almost no effect on the maximum power density when it exceeds 12 ml min^{-1}, and lower flow rates result in lower maximum power densities under the same concentration, especially when the driven load is above 100 mW cm^{-2}.

3. Controller construction

A controller is designed to trace the MPP of DMFC stacks by adjusting the operating conditions according to the driven load. The flow rate is kept 12 ml min^{-1} in the following simulation based on the aforementioned discussion.

The tasks of the controller include 1) calculating the work current density using Eq. (1) to shift the operating point of the stack and 2) selecting a suitable methanol concentration to keep the DMFC working at its MPP.

Fig. 4 shows a schematic of the proposed controller.

3.1. *Increment output mode fuzzy controller*

Because the DMFC is a large-time-delay, complex system, an improved fuzzy controller-increment output mode fuzzy controller

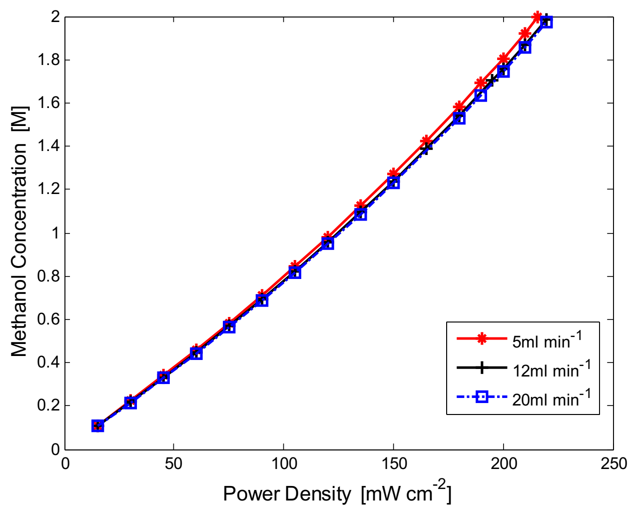


Fig. 3. Relationship between concentration and maximum power density.

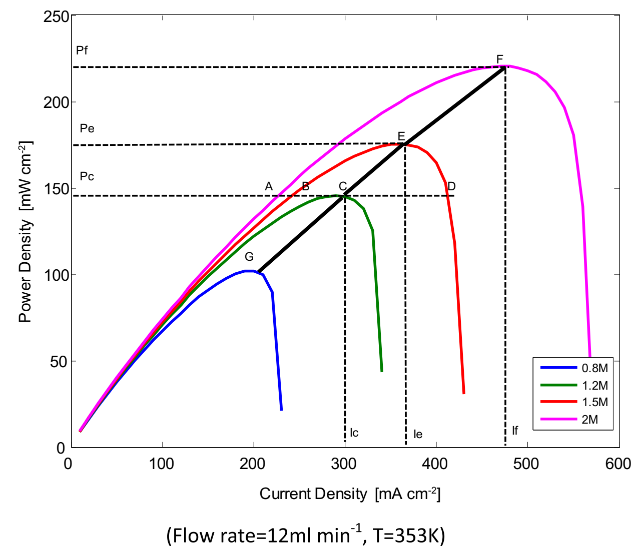


Fig. 5. Example of DMFC MPP shift.

(IOMFC) [23] is introduced to control the work current density and methanol concentration.

Similarly to a basic fuzzy controller, the IOMFC uses the error and error change rate of the controlled variable as input and processes the input variables based on the general fuzzy sets and rule base [24] in an attempt to eliminate the error. Unlike a basic fuzzy controller, the result of the fuzzy processor is processed as follows before being applied to the controlled object.

$$u_{c(i)} = u_{c(i-1)} + K_{c1}\left(f_{(i)}\left(e_{(i)}, ec_{(i)}\right) - f_{(i-1)}\left(e_{(i-1)}, ec_{(i-1)}\right)\right) + K_e e_{(i)} \quad \left|e_{(i)}\right| < \delta \tag{3}$$

$$u_{c(i)} = u_{c(i-1)} + K_{c2} f_{(i)}\left(e_{(i)}, ec_{(i)}\right) \quad \left|e_{(i)}\right| > \delta \tag{4}$$

To ensure that the control process is smooth and fast, the IOMFC selects different control modes according to the error: when the absolute error is larger than the threshold δ, Eq. (4) is selected; when the absolute error is less than the threshold δ, Eq. (3) is selected.

The IOMFC can cause the controlled signals to gradually approach the expectation value by tuning the control signal continuously based on fuzzy operation, which draws on human control behavior. The introduction of IOMFC can simplify the control process while ensuring accuracy, even for large-time-delay, complex systems.

3.2. Control of current density

To keep the DMFC working at its MPP, the work current density must be regulated when variations in the driven load occur. In this paper, a DC/DC converter, which is located between the DMFC stack and the driven load as shown in Fig. 6, is used to shift the work point to control the current density of the DMFC [15,16], and the current density is given by the following equation:

$$I_{FC} = V_{FC}/(1-d)^2 R_L A \tag{5}$$

where I_{FC} (mA cm^{-2}) and V_{FC}(V) are the output current density and voltage of the DMFC, respectively; d is the duty cycle of the PWM signal; R_L (kΩ) is the resistance of the driven load; and A (cm^2) is the cross-sectional electrode area of the DMFC.

To force the DMFC to always work at its MPP, the IOMFC iteratively calculates the reference current density using Eq. (1) and regulates the duty cycle of the PWM signal of the converter based on the error and error change rate of the reference current density and the work current density followed by the change of the driven load. When the work current density coincides with the reference value, the operating point of the DMFC will be an MPP corresponding to the driven load.

3.3. Control of the concentration

From Fig. 5, it is clear that the same power density Pc (e.g., points A, B, C, and D) can be produced under different concentrations and that the concentration corresponding to the point C, which is an MPP, is the lowest. The DMFC cannot produce enough power to drive the load when the concentration is lower than point C (e.g., point G), while when the concentration is higher than point C (e.g., points A, B, and D), the DMFC produces a higher power density than

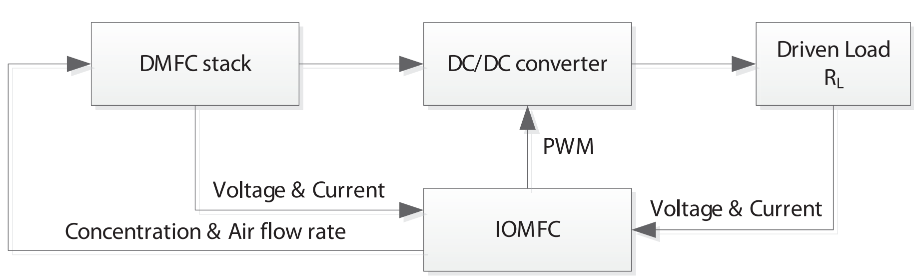


Fig. 4. Schematic of the DMFC controller.

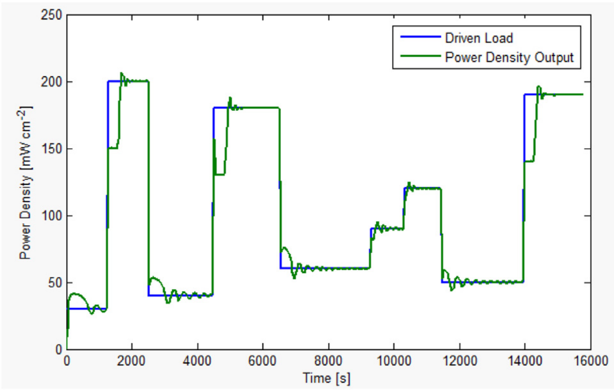
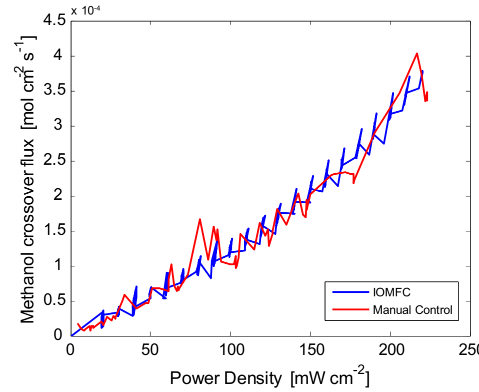
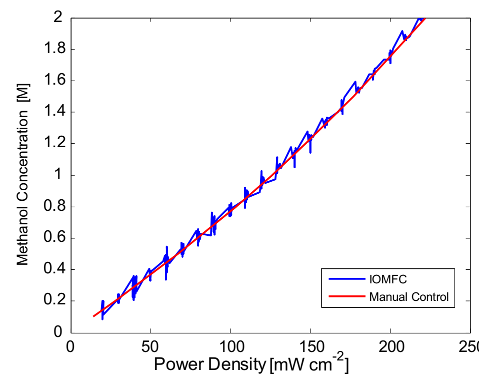


Fig. 6. Power density responses to step changes in driven load.



(a) Comparison of crossover under different power density



(b) Comparison of methanol concentration under different power density

Fig. 8. Comparison of IOMFC control and manual control.

the load needed at the work current density calculated by Eq. (1). Thus, keeping the DMFC work current density equal to the result of Eq. (1), we can keep the DMFC work at an appropriate MPP by adjusting the concentration to ensure the DMFC output power and the driven load are same.

When the driven load increases (from Pc to Pe), the DMFC work current density will be forced to increase until it shifts from Ic to Ie. Only by increasing the concentration can the output power density approach the driven load, and once the output is equal to the driven load, the MPP shift is completed (from point C to point E). In the same way, the DMFC can shift its work point from point E to point C by decreasing the concentration when the driven load decreases. Thus, the work point of the DMFC can be shifted between different MPPs by adjusting the concentration.

Based on the error and error change rate between the driven load and real output of the DMFC, the IOMFC can continuously adjust the concentration, followed by the variation in driven load, to ensure that the DMFC always operates at an appropriate MPP.

4. Simulation results and discussion

Fig. 6 shows that the power density can follow the step change of the driven load and enter a steady state after a long regulation time (approximately 200–500 s). We also notice that the power density overshoots when rapid driven load changes occur. As seen from Fig. 7, there always exists a lag time between the change in concentration and the change in power density regardless of how the driven load changes due to the slow electrochemical kinetics of methanol oxidation and the slow methanol diffusion and convective transport mechanism. The existence of a large time-delay complicates the control process and causes power density overshoots and fluctuations.

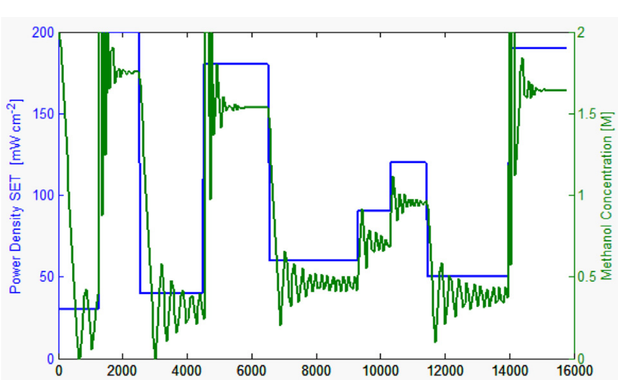


Fig. 7. Concentration responses to step changes in driven load.

Fig. 8 compares the methanol crossover flux and the concentration of the selected MPPs with the IOMFC control results under different power densities. The results prove that the controller can keep the DMFC operating at its MPP by adjusting the work current density and methanol concentration dynamically in response to a change in the driven load. As mentioned earlier, the concentration is always the lowest when the DMFC operates at MPP. For the air flow rate is proportional to the methanol concentration, the power consumption of air pump will also be the lowest.

5. Conclusion

In this paper, the effect of concentration, methanol solution flow rate, and current density on DMFC performance was analyzed based on a simulation model. The results showed that an increase in flow rate does not affect the maximum power density and methanol crossover rate when it is beyond a specific threshold. Though a low flow rate can reduce the power consumption of the recirculation pump, but a higher concentration is needed to maintain the power output. A higher concentration will increase the methanol crossover leak and that causes loses in performance.

In this paper, a fuzzy controller is introduced to adjust the DMFC work current density and concentration dynamically following the driven load. The simulation results show that the controller can ensure that the DMFC constantly works at its MPP. With the aid of the fuzzy controller, the methanol concentration and crossover rate are always the lowest for the driven load. Because the air flow rate

is proportional to the concentration, the lowest concentration also leads to the lowest power consumption by the air pump.

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